

HYDROGEOLOGIC MODEL OF A LEACHATE PLUME IN AN UNCONFINED
COASTAL PLAIN AQUIFER AND CHEMICAL TRANSPORT MECHANISMS
OF METALS AND DENSE NON-AQUEOUS PHASE LIQUIDS

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Hydrogeologic Model of a Leachate Plume in an Unconfined Coastal Plain
Aquifer and Chemical Transport Mechanisms of Metals and Dense
Non-Aqueous Phase Liquids

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By
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ABSTRACT

Groundwater contamination is of increasing environmental concern as many aquifers across the globe have experienced a decrease in water quality in recent time. The growth of the world's population over the last couple of decades has caused a dramatic increase in the rate of groundwater use. One potential source of groundwater contamination is waste material in landfills. The 1st Division Road Sanitary landfill at Fort Benning Military Reservation was studied to evaluate the potential effect on local groundwater and a leachate plume was recognized using data from 16 groundwater monitoring wells located around the facility. The study site is located in the Coastal Plain Province. The area includes undeformed detrital sedimentary strata of Upper Cretaceous age, formed in coastal and marine environments. Three stratigraphic formations are present at the study area: the Tuscaloosa Formation, the Eutaw Formation and the Blufftown Formation. A three-dimensional mathematical model (MODFLOW/MT3D) was used to simulate the regional groundwater flow and contaminant transport at the site. This model was then used to investigate the migration of chlorinated hydrocarbons (CHCs) and metals in unconfined high porosity sandstone, indicating that migration for both CHCs and metals were caused by advective transport. In addition, the results also indicated that CHCs migrate by the process of diffusion. However, due to the distance to potential surface receptors as well as dilution, dispersion and retardation, it is predicted that no detectable pollutants will reach surface streams.



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ACRONYMS

ATSDR	Agency for Toxic Substances and Disease Registry
bgs	Below Ground Surface
CEC	Cation Exchange Capacity
CESAS	Savannah District, US Army Corps of Engineers
CHC	Chlorinated Hydrocarbons
CoE	Corps of Engineers
CWA	Clean Water Act
EPA	Environmental Protection Agency
GAEPD	Georgia Department of Natural Resources, Environmental Protection Division
GCL	Geosynthetic Clay Liner
HDPE	High Density Polyethylene
MCL	Maximum Contaminant Level
mgd	Million Gallons per Day
mg/L	Milligrams Per Liter
ug/L	Micrograms Per Liter
MSL	Mean Sea Level
MYA	Million Years Ago
OECD	Organization for Economic Development
PVC	Polyvinyl Chloride
QA	Quality Assurance
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RFI	Resource Conservation and Recovery Act Facility Investigation
SDWA	Safe Drinking Water Act
SVOC	Semi-volatile Organic Compound
SWLF	Solid Waste Landfill
SWMU	Solid Waste Management Unit

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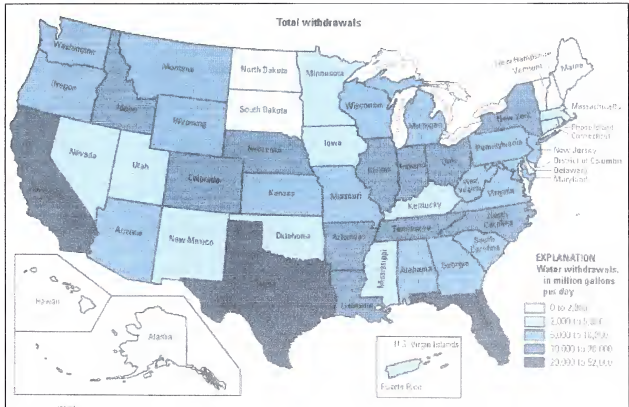
TMC	Troop Medical Clinic
TPH	Total Petroleum Hydrocarbon
USAEHA	US Army Environmental Hygiene Agency
USACHPPM	US Army Center for Health Promotion and Preventative Medicine
USGS	US Geological Survey
VOC	Volatile Organic Compound

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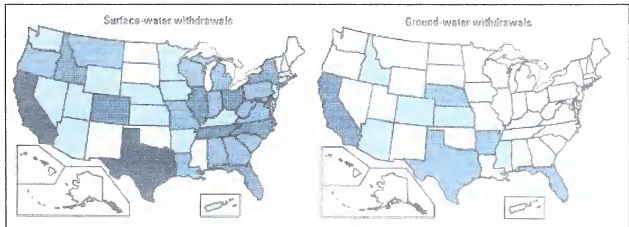
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INTRODUCTION

Subsurface contamination is an increasing environmental problem. During the last decades, the world's population has steadily increased. Many urban environments have experienced a very dramatic population growth. The intensified pressures from areas with high population density have placed severe stress on many infrastructures, especially water supplies. For 50% of all Americans (including 95% of the rural population), groundwater is the primary source of drinking water (U.S. EPA 1996). The geographic distribution of total water, surface water and groundwater withdrawals, for public supply in the United States is shown in Figure 1. Groundwater provides about 37 percent of the Nation's public water supply (USGS 2004a). The figure shows that groundwater is an important source of drinking water in every State. This clearly makes water one of the most important natural resources in the United States. However, this is not only true for the U.S. Similar numbers are observed in all parts of the globe. As a result, groundwater overdevelopment is becoming increasingly evident around the world (Shah et al. 2000). Over the last century, many groundwater reserves have thus experienced a severe reduction in volume due to excessive pumping, and some reserves have even been totally depleted. In addition, increased use of chemicals and solvents in both industrial processes as well as private home use has led to a decrease of water quality in many areas of the world. It is currently estimated that 25% of the available groundwater in the United States is contaminated (Geophysics Study Committee 1984). The importance of source-water management to protect drinking water is therefore a major global issue.



A



B

Figure 1 (A) Geographic distribution of total water withdrawals by public sources in the U.S. (B) Geographic distribution of total surface water and total groundwater withdrawals. Figure based on data from 2000. Source: USGS (2004b).

Scientific assessments of potential groundwater contamination from anthropogenic sources have intensified in the last decade (OECD 1991). This has led to an increase use of groundwater flow and transport models as tools in vulnerability assessments. These models allow for a comprehensive three-dimensional conceptualization of groundwater behavior, including geochemical and biological processes. Due to the nature of groundwater, contamination must be approached differently from surface water pollution. Larger reservoir sizes (aquifers) and the longer residence times associated with groundwater make contaminants difficult to remediate. Treating groundwater contamination is often cost prohibited due to the depth and the expense of drilling. Furthermore, groundwater differs greatly from surface water in regards to flow patterns. Stream flow is linear and channelized, which cause stream water to display only one flow direction. Groundwater, however, exhibit a more complex pathway. Both the hydraulic gradient and the hydraulic conductivity of the sediment determine the direction of groundwater flow. Therefore, groundwater simultaneously moves both horizontally as well as vertically, generating a 3-dimensional flow pattern (Figure 2). Subsurface contamination can therefore become a persistent problem as remediation efforts are made difficult.

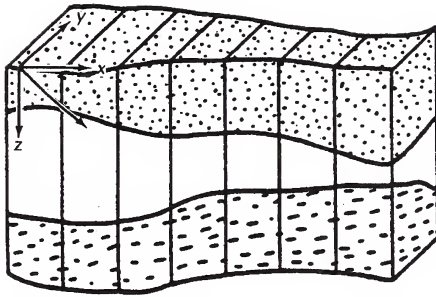


Figure 2 Generalized block diagram of 3-D groundwater flow in x, y and z direction. Resulting arrow indicates overall flow direction. Modified from Waterloo Hydrogeologic, Inc. (1999).

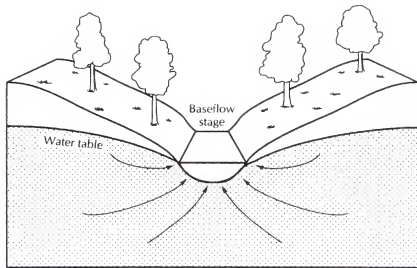
Groundwater can dilute and thus accept more contamination, compared to surface water, before it reaches critical levels. However, due to the complex movement of groundwater, the removal of contaminants is a very slow and arduous process. Moreover, if multiple harmful substances contaminate the groundwater, there is a strong possibility that they will interact with each other, further complicating remediation efforts. Consequently, it is simpler and less expensive to protect water above ground, before it becomes contaminated. Rather than dealing with subsurface pollution, where “multi-approach remediation strategies” are needed (Wycisk et al. 2003), direct source control is preferred. In addition, groundwater plays an important part in many ecosystems. Groundwater contamination correlates directly to the diversity and richness of biota in

various regions. Numerous streams and rivers in the world are supplied by groundwater, especially during droughts. It is, therefore, important to maintain high-quality groundwater in order to assure good-quality stream water.

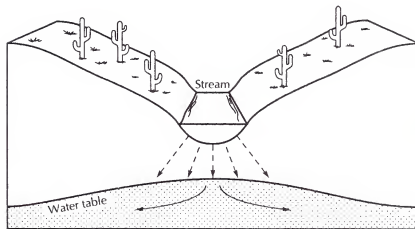
Three-dimensional groundwater flow and transport models are used to analyze complex hydrogeologic environments. One example of such an environment is solid waste disposal sites. If waste buried in a landfill comes in contact with water percolating down from the surface, potential contaminants can dissolve and mix with the water. This liquid containing dissolved metals, organic compounds and inorganic compounds is known as leachate. Leachate from landfills is a severe environmental problem, as it can migrate downward from the landfill into the groundwater and cause groundwater contamination. According to the national water quality inventory report produced by the U.S. Environmental Protection Agency (EPA), municipal landfills were listed by more than 35 states as a major threat to groundwater quality (1990). Groundwater that contains dissolved volatile organic compounds (VOCs) are commonly found in the leachate plumes originated from landfills (Christensen et al. 1994).

A particular problem exists under unlined landfills. Today, the U.S. EPA requires all solid sanitary waste landfills (SWLF) to be lined. As the solid wastes undergo chemical decomposition, soluble as well as insoluble compounds are released. Infiltrating rainwater will then aid in the downward movement of the contaminants. The leachate will ultimately be transported to the groundwater, where different processes cause migration and dispersion. Over time a concentrated source of contaminants will

migrate outward, creating a plume that mainly moves with the direction of the groundwater flow. It is important to understand that groundwater and surface water are closely interrelated. It is sometimes difficult to separate the two because they replenish each other. One of the most important interplays between groundwater and surface water is baseflow. Baseflow is characterized by groundwater seeping into a stream channel. Subsurface water can therefore be responsible for maintaining the hydrologic balance of surface streams, springs, lakes, wetlands and marshes (Fetter 2001). The amount of baseflow a stream receives is closely linked to the permeability of the rock or the soil in the watershed. During periods of severe droughts when the water table level is below the flood-crest depth of streams, water can flow from streams and lakes into the ground (Fetter 2001). Figure 3 shows cross sections of gaining and losing streams. This interaction between groundwater and surface water is why one can contaminate the other. It is therefore easy to see how leachate from landfills can spread to uncontaminated areas and thus affect other receptors, such as surface water and drinking water.



A



B

Figure 3 (A) Cross-section of a gaining stream where groundwater recharges stream. (B) Cross-section of a losing stream where stream water recharges groundwater. Source: Fetter (2001).

Elevated contaminant levels in the groundwater beneath landfills at Fort Benning, GA have been documented in groundwater monitoring reports. The Savannah District, US Army Corps of Engineers (CESAS) and other government agencies have conducted groundwater sampling and analysis at all landfills located at Fort Benning. Groundwater

sampling has been conducted annually or bi-annually from groundwater monitoring wells located within the water table. This study investigated a single landfill-derived contaminant leachate plume in unconfined high porosity sandstone in this region. The landfill is unlined on the bottom but does have an impermeable geotextile liner cover overlain with two feet of clay. The results from sampling dating back to 1996 shows elevated levels of several VOCs and metals in the groundwater. A particular VOC, namely chlorinated hydrocarbons (CHC), cause a distinctive problem as they continuously were detected in levels above maximum contaminant levels (MCL). MCLs are established by the EPA under the Safe Drinking Water Act (SDWA) and are legally enforceable standards that apply to public water systems.

The specific objectives of this investigation are: (1) to construct a site specific groundwater flow model by using Visual MODFLOW 2.8.2, (2) to construct a contaminant transport model (using MT3D) showing the distribution of selected CHCs and selected metals (Table 1), and (3) to determine what processes influence rate and directions of contaminant transport and the fate of the leachate plume for this site. Understanding the interplay of the processes at work in contaminant transport allows better predictions in how to minimize the release and impact of harmful substances. In addition, understanding distribution patterns and migration of contaminants will be valuable in future risk assessment.

Table 1 Chlorinated hydrocarbon compounds and metals included in research.

CHCs	Metals
Methylene Chloride	Lead
Vinyl Chloride	Mercury
1,1-Dichloroethene	Zinc
1,1-Dichloroethane	
Trichloroethene	
Tetrachloroethene	
Trichlorofluoromethane	

DESCRIPTION OF THE STUDY AREA

Regional Geologic Settings

The study area is located just south of the Fall Line. The Fall Line is a geological boundary about twenty miles wide that runs across Georgia northeastward from Columbus to Augusta. This former Late Cretaceous, 99 to 65 Million Years Ago (MYA), shoreline of the Gulf of Mexico separates the Coastal Plain to the south from Piedmont Province to the north. The Piedmont Province is a highly structurally complex region. The area is characterized by high-rank metamorphic and plutonic igneous rocks, which mainly date back to the Paleozoic (543 to 248 MYA). These rocks exhibit very low initial porosity in unweathered areas. Fracture porosity does exist but decreases with depth. Outcrops of Piedmont rocks are exposed in the Chattahoochee River Channel in Columbus but can also be observed in other areas around the north Columbus area such as Flat Rock Park.

The Coastal Plain Province in Muscogee and Chattahoochee Counties essentially includes undeformed sedimentary strata of Upper Cretaceous age (146 to 65.5 MYA) that dip and thicken to the south and southeast (Figure 4). The sediments are composed mainly of detrital sandstone and mudrocks formed in coastal and shallow marine environments. The strata are generally poorly consolidated, with thin, iron-oxide cemented hardpan zones usually within sandstone beds. The strata are exposed in the study area where it dip generally southward with dip angles of 2 or 3 degrees, up to around 5 or 6 degrees. South of the study area, the Cretaceous formations strata dip beneath Tertiary (64 to 1.6 MYA) strata.

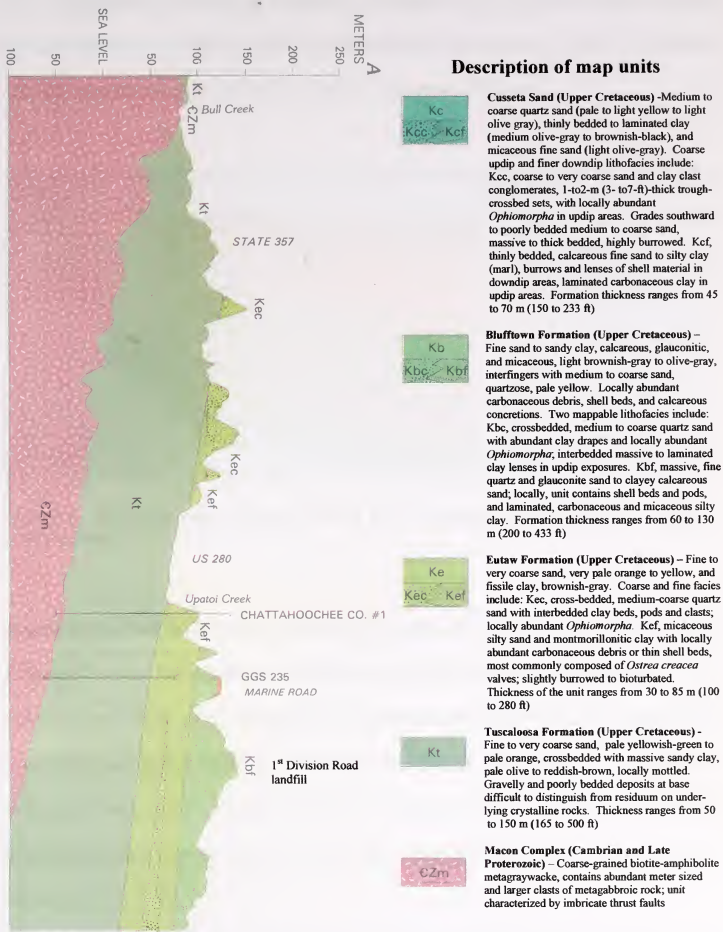


Figure 4 Cross-sectional view of the study area. Vertical exaggeration X 20. 1:100,000. Source: Reinhardt et al. (1994).

Collectively, Cretaceous formations comprise the Cretaceous aquifer system, which is generally unconfined in the outcropping areas but becomes a confined aquifer in downdip areas where it is overlain by Tertiary formations (Figure 5).

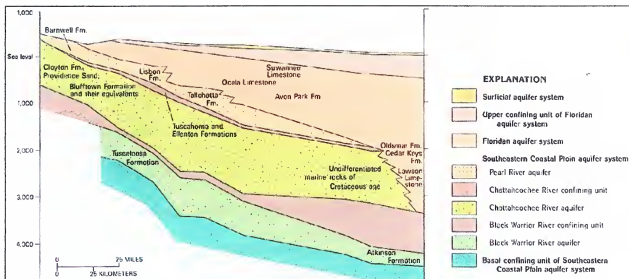


Figure 5 Hydrogeologic section showing the Cretaceous aquifer system. Source: USGS (1990).

Coastal Plain strata in the study area are approximately 612 feet thick, based on the core extracted from the United States Geological Survey's (USGS) well Chattahoochee CO #1 (Marsalis and Fridell 1975, Appendix A). These strata overlay a basement composed of crystalline rock, similar to those of the Piedmont north of the Fall Line. The crystalline bedrock is composed of Precambrian gneiss and schist and, thus, exhibit low porosity and low permeability. Groundwater flow is therefore limited but is enhanced by fractures in the rock.

In the vicinity of the landfill, the Coastal Plain consists of three formations: the Tuscaloosa, Eutaw and Blufftown Formations. The Tuscaloosa Formation is the oldest

unit of the Coastal Plain in the western Georgia-eastern Alabama area and forms the basal sedimentary unit. This formation is composed of sediments about 250 feet thick and consists of alternating beds of silty mudstone and sandstone. The Tuscaloosa includes numerous fining-upward stratigraphic sequences (Frazier 1987). Each sequence begins with a local erosional disconformity and is composed of coarse to gravelly, cross-bedded to massive bedded sandstone grading upward into massive, maroon and gray mottled, silty sandstone. The sandstone layers are moderately to poorly sorted and range from conglomeratic sandstone to coarse arkosic sandstone, commonly crossbedding and semi-indurated (CESAS 1999). The fining-upward sequences are interpreted as fluvial point-bar sequences formed by meander migration on a fluvial plain (Frazier 1987). Hydrologically, each fining-upward sequence consists of sandy strata with moderately high porosity and hydraulic conductivity overlain by mudstone layers of low initial porosity but moderate fracture porosity. Occasional sandy clay lenses occur within the sandstone even though it is not a typical feature.

The Eutaw Formation overlies the Tuscaloosa Formation and outcrops of the formation are mainly evident in the banks and valley walls of the Chattahoochee River, Upatoi Creek and their tributaries. In this area, the Eutaw Formation is 30 to 45 m (100-150 ft) thick and is composed of several lithologies (Reinhardt 1980). The boundary between the two formations is a major erosional disconformity. The nature of the Eutaw strata changes from north to south. Northern exposures are composed mainly of coarse, cross-bedded, poorly consolidated fine to coarse sand with minor interbeds of claystone and rare iron-oxide cemented layers. These strata exhibit high initial porosities and

hydraulic conductivities. Southern exposures of the Eutaw are composed of a lower unit of coarse, cross-bedded sandstone similar to updip Eutaw strata overlain by interbedded fine to very fine sandstone and poorly sorted silty mudstone. This strata can in some horizons become very clayey. For this reason, the middle and the upper parts of the Eutaw act locally as an aquatard. Muddy Eutaw strata are typically fossiliferous, containing mainly molds and casts of marine mollusks and other invertebrates. Because of this, these layers feature significant moldic porosity. The Eutaw Formation, at the study area, consists of a basal coarse sand overlain by a dark gray, soft siltstone or shale that is interbedded with thin layer of white fine sand. Toward the east, this interbedded shale and sand pinch out to give away to a more coarsely sorted sand. The sand weathers pale to reddish brown and can sometimes resemble the Tuscaloosa. In general, the Eutaw sand weathers to a deeper shade of red, orange, or reddish-brown than the Tuscaloosa. In addition, the clay beds of the Eutaw Formation are not as intensely mottled with purple as the Tuscaloosa Formation. The Eutaw strata represents deposition in coastal environments, with coarse updip strata representing estuarine bars, bay-head deltas and shallow shelf conditions (Frazier 1987, Reinhardt 1980). The formation exhibits abrupt coarse to fine lithofacies changes both laterally and vertically (Reinhardt et al. 1994). Because middle and upper Eutaw strata are significantly less permeable than Blufftown sands, it forms the aquiclude at the base of the Blufftown aquifer in the study area. Rainwater percolates downward until it reaches the less permeable Eutaw Clay and collects on top of the Eutaw Formation, residing within the Blufftown.

The Blufftown Formation overlies the Eutaw Formation and is the youngest sedimentary bed in this region. The strata forms the basal subdivision of the Ripley formation and is locally overlain by the Cusseta sand. The Blufftown outcrop belt thins eastward where the bed becomes difficult to distinguish from the Cusseta sand (Reinhardt 1980). The outcrop belt is present from the Chattahoochee River valley to the Flint River. Lithologic heterogeneity is greatest in the Chattahoochee River. In the valley area, the unit is 120 to 180 m (400-600 ft) thick in its broad outcrop belt (Reinhardt 1980). The formation grades laterally into eastern Alabama, where it intertongues with the Mooreville chalk and the basal part of the Demopolis chalk (Eargle 1955). The upper portion of the formation differs slightly in composition compared the deeper deposit. The top unit, about 45 m (150 ft) in thickness, contains alternating beds of sand and sandy carbonaceous highly micaceous clay overlying a lower unit of crossbedded coarse sand (CESAS 1999). The clay members are laminated, dark-gray marine clays (some carbonaceous) containing abundant soft, thin fossil shells (Eargle 1955, Reinhardt 1980). The upper part of the Blufftown is poorly preserved in the area. The basal portion of the formation can contain as much as 45 m (150 ft) of crossbedded sand (Reinhardt 1980). This portion of the unit locally contains the trace fossil *Ophiomorpha* (Frazier 1987). In the study area, only the lower portion of the Blufftown is present and consists for the most part of medium to coarse sandstone. This portion of the formation is described by Reinhardt as “glauconitic calcareous fine sand to micaceous clay and marl” (1980). The basal sand forms conspicuous ridges and is responsible for the high sandhills that

characterize the Harmony Church area. Ledges of this basal sand cemented by iron oxide form most of the landmarks in the area (Eagle 1955).

Topography and Hydrology

The 1st Division Road Sanitary landfill consists of a 61.1 acres area located on the southeast corner of the intersection between Victory Drive (Routes 280/27) and 1st Division Road in the Harmony Church Area of Fort Benning Columbus, GA (Figure 6). Landfill operations began in 1985 (USAEHA 1994). The project area prior to 1985 hosted the Manila Heliport. The study area has also hosted a troop medical clinic (TMC) that operated during WWII and served soldiers living and training in the area. The clinic was composed of three buildings with a nearby heliport. Most of the clinic was damaged by fire after WWII and the entire site was demolished in the early 1950's.

The area is bounded immediately to the west by an asphalt road. The surrounding area is relatively undeveloped and pine woodlands are present in all directions of the landfill. The only buildings present are located on the west side of the landfill and comprises the Natural Resources Complexes. The landfill site is located in an area of moderate topographic relief (Figure 7). Elevations range from approximately 465 feet above mean sea level (MSL) to approximately 400 feet above MSL. The elevation of the landfill is above the floodplain of local surface streams. Figure 8 shows the topography of the study site. The slopes in all directions are grassed and the surrounding area is predominately woodlands. The study site lies within the Ochillee Creek watershed and drainage is to the east. Ochillee Creek is a tributary of Upatoi Creek and flows generally

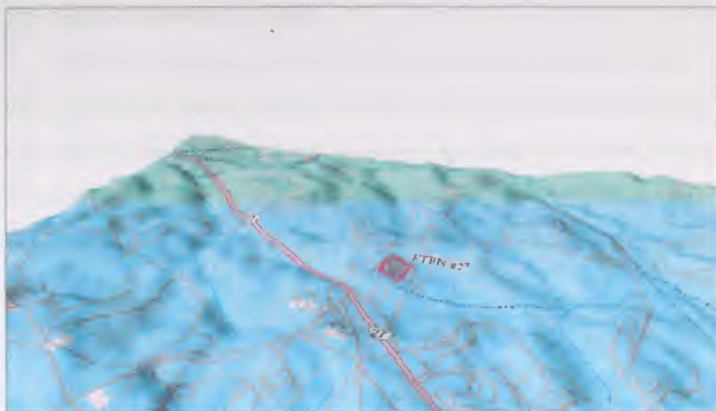
northwest about 1.3 miles northeast of the site at its nearest location. In addition to the major streams in the area, numerous seasonal streams north and west of the site drain ultimately into Upatoi Creek.

The landfill study area is situated over an aquifer that ranges in depth from 40 to 90 feet below the ground surface and becoming more shallow to the east. Groundwater is hydraulically connected throughout the Upper Cretaceous deposits (CESAS 1996). The total thickness of the aquifer is about 750 feet.

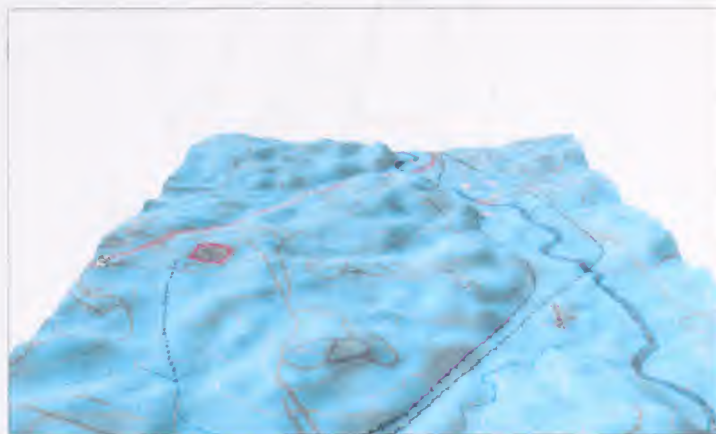
Shallow perched groundwater is also present in this area. This water is closely associated with laterally discontinuous strata. These series of alternating lenses of clay, silt and sand either holds water within the layer or causes areas with perched water. Groundwater depths in the surficial aquifer generally follow the topography. The groundwater flow in this aquifer mainly follows the surface water flow direction. Groundwater in the deep (artesian) aquifer is contained in beds of gravel or sand and is separated from the shallow aquifer by confining layers of fine-grained, less permeable deposits (CESAS 1999).



Figure 6 Location of 1st Division Road landfill. 1:25, 000. Source: Army Map Service, Corps of Engineers (1954).



A



B

Figure 8 Topographic features of the study site. 1st Division Road landfill outlined in red. (A) Area viewed from the South. (B) Area viewed from the East. Vertical exaggeration X 4. Figure prepared using Delorme 3-D TopoQuads: Georgia (1999).

HISTORY OF THE STUDY AREA

In 1983 Fort Benning was issued a Resource and Conservation Recovery Act (RCRA) Subtitle D permit by the State of Georgia, which allowed the construction and operation of a sanitary landfill at its current location. The design of the landfill included four areas or cells (Figure 9). Cells one and two were used for waste disposal as soon as the landfill became operational. Cells three and four, however, were saved for future use.

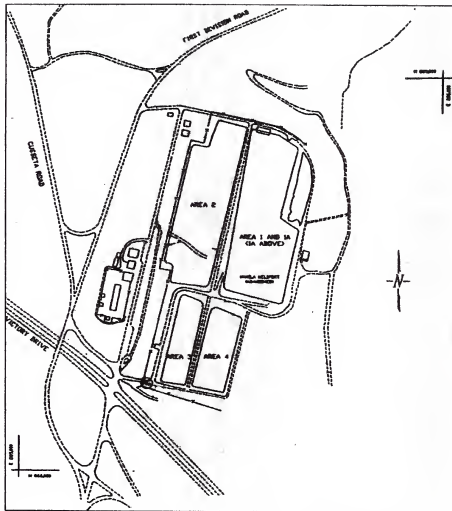


Figure 9 Design of 1st Division Road landfill showing the four cells. Source: USAEHA (1994).

In July 1, 1998, when all waste disposal operations ceased, cell three and four were still unused. Of the initial 61.1 acres designated for waste disposal, only an estimated area of 48 acres was therefore used. During landfill operations, cells one and two accepted approximately 175 tons of waste on a daily basis and hold an estimated 500,000 tons of waste in total. While operating, a modified area-fill technique was employed at the landfill, using slope method to fill individual cells. This provided daily cover for the active cells. The northeastern corner of area two was the last portion of the landfill to receive debris. Fort Benning has a large family housing population as well as a transient population of soldiers. This has led to an atypical waste profile of the 1st Division Road landfill that is somewhat different from many other large municipal sanitary landfills. It is estimated that 40 to 50 percent of the waste in the landfill is composed of non-organic waste, which are higher volumes than observed for a landfill serving large municipalities (Unpublished data, personal communication, Dorinda Morpeth 2004). Landfills serving cities generally have a higher percentage of organic waste resulting from food business, industry and household. This unique population composition produced waste from building demolition, miscellaneous military items and military training.

On July 19, 1996, the State of Georgia Department of Natural Resources, Environmental Protection Division (GAEPD) issued a Hazardous Waste Facility Permit to Fort Benning. This permit gave raise to a change of the definition for the 1st Division Road landfill. Under this permit, the landfill became classified as a solid waste management unit (SWMU) and required a full RCRA investigation. The area was

assigned a SWMU identification number, namely FTBN-027. As part of the RCRA Facility Investigation (RFI), the four existing wells installed for groundwater evaluation before the landfill was built (W-A, W-B, W-C, W-D) and the wells (P-series) installed by USAEHA were brought up to current GAEPD standards, and redeveloped (CESAS 2001).

After use of the waste site was discontinued, the 1st Division Road landfill underwent closure and a closure plan was submitted to the State. A low-permeability layer consisting of a high-density polyethylene (HDPE) geomembrane cap overlies a geosynthetic clay liner (GCL), which provides a near-imperious barrier. The two feet of soil cover was excavated from the area where cell three and four were designated. This area today hosts an open burrow pit. The soil cover was followed by a layer of top soil and seeded with grass. As part of the closure plan, passive methane vents were installed on the top of the landfill to allow the release of methane accumulation beneath the landfill cap.

The main water supply for Fort Benning comes from Upatoi Creek. The intake for the water treatment plant is located about 4.5 miles west from the landfill. The current surface water permit limits the amount of creek water that can be withdrawn daily. The water withdrawal limit is 10 million gallons per day (mgd) as a monthly average, with 12 million gallons per day allowed in any 24-hour period (provided the monthly average is not exceeded). The average daily flow of Upatoi Creek is 197 ft³/sec (based on 34 years of record). Figure 10 shows the daily mean stream flow for Upatoi

Creek during the majority time period of the sampling phase. Most usage by Fort Benning is for domestic use and for fire fighting.

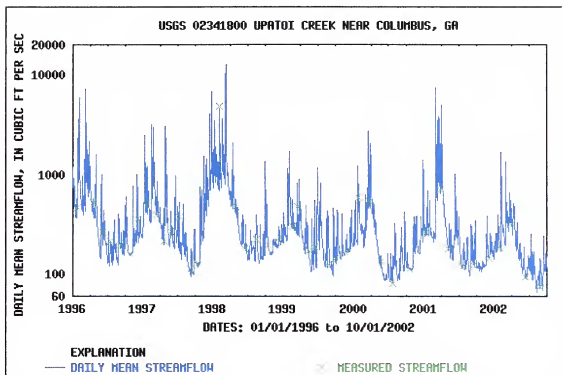


Figure 10 Daily mean stream flow for Upatoi Creek. Graph shows a period of record from 1996-01-01 to 2002-09-30. Source: USGS (2004c).

Although Fort Benning's water supply comes out of Upatoi Creek and the large groundwater reserve is not used as a freshwater supply, Fort Benning is conducting groundwater sampling as required by the EPA. The groundwater must meet federal drinking water standards under the Clean Water Act (CWA) to be considered contaminant free. Before the landfill was built, four permanent wells were installed in order to test the hydrological characteristics. These wells were designated W-A, W-B, W-C and W-D. In 1993, the US Army Environmental Hygiene Agency (USAHEA-today named U.S. Army Center for Health Promotion and Preventative Medicine-

USACHPPM) conducted an investigation of the landfill area. This investigation led to the installation of ten additional groundwater wells around the landfill. These wells constitute today the P-series (P-1 through P-10). During the RFI in 1996, all the existing groundwater wells (W-A, W-B, W-C, W-D and P-series) were redeveloped to fit current GAEPD standards (Appendix B).

In 1996, a new groundwater monitoring plan was develop by Polyengineering, Inc. for the 1st Division Road landfill. This plan called for a more extensive network of wells in order to detect possible contamination. In accordance with this plan, eight new wells were installed around the two active cells (GWA-1, GWA-2, and GWC-1 through GWC-6, Figure 11). Today, the area hosts 48 groundwater wells.



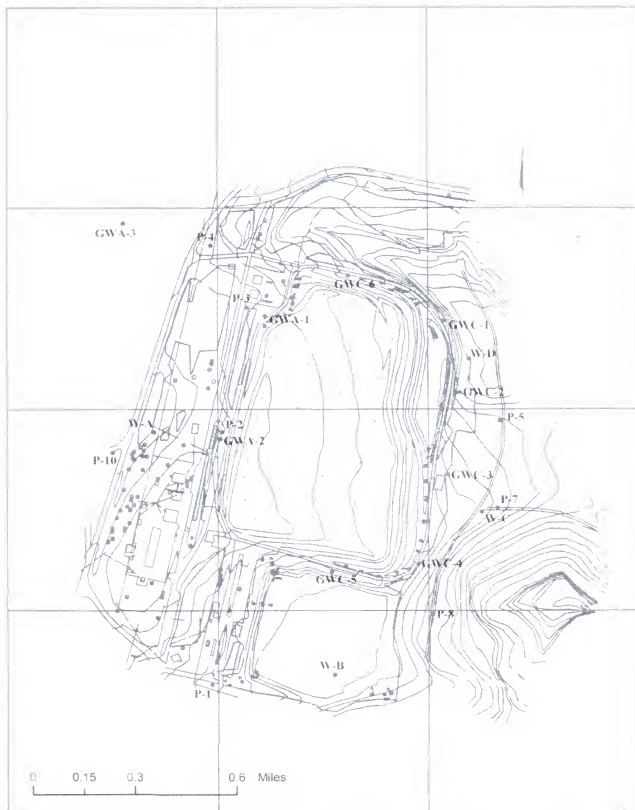


Figure 11 Location of groundwater monitoring wells at 1st Division Road landfill. Map only show wells developed through 1996. Source: CESAS. Figure modified using ArcGIS 8.0.

Figure 1. Location of the study area in the north of Iran. The map shows the location of the study area in the north of Iran. The map also shows the location of the study area in the north of Iran.

METHODOLOGY

Sampling Technique

All the groundwater monitoring wells and the piezometers found in the area of FTBN-027 were drilled and installed by the Savannah District of the U.S. Army Corps of Engineers. All boreholes were drilled using a 6-inch, outer-diameter, hollow stem auger. The borings were drilled to a depth between five and 10 feet below the water table. No drilling fluids were used during the drillings. All wells were constructed using a 2-inch, inside diameter, polyvinyl chloride (PVC) well casing and preslotted well screen (0.010-inch slot size with flush-threaded joints). The annulus surrounding the well screen was sand-packed with clean, dry medium to coarse sand. A 2- to 3-foot bentonite seal was placed above the sand pack and hydrated with distilled water. The remaining space was filled with cement within 3 feet of the surface. This was topped by a thin layer of bentonite pellets to the surface layer. This provides a flexible cap around the well that will give if frost heave pushes the well pad up. A steel protective casing with hinged locking cap was installed around the PVC well casing. Before any sampling occurred, the wells were developed by purging the groundwater. Groundwater samples were collected as soon as the well recovered after purging. All the groundwater samples were collected and packaged using standardized field procedures. All samples were analyzed for total metals, VOCs, SVOCs, and TPH. Volatiles and metals were preserved with HCl and HNO₃, respectively. All the samples were capped, labeled and stored in a cooler to keep the temperature at or below 4 degrees Celsius. Two sets of samples to be analyzed for metals were obtained from each well. An unfiltered sample was collected to be

compared to the MCLs. A filtered sample was used to analyze if leachate from the landfill was affecting any of the other monitoring wells. Duplicate samples and quality assurance (QA) samples were collected and stored in the same manner. All samples were shipped by overnight express to designated laboratories.

The U.S. Army Corps of Engineers, Savannah District has conducted groundwater monitoring tests since 1996 according to the GAEPD Subtitle D permit. Wells around the 1st Division Road landfill have been sampled semi-annually. This investigation analyzed the data contained within the groundwater monitoring reports prepared after each sampling event. Groundwater samples were analyzed from 16 wells (Table 2). Even though additional groundwater wells are present around the landfill, these were omitted since the sampling data are not continuous. All wells were screened in the Eutaw formation.

The results from 8 years of groundwater monitoring have been relatively consistent. Several VOCs were detected in the samples throughout this period, many of them exceeding their MCLs. The most commonly detected compounds with the highest concentrations were CHCs. In order to generate a transport model this research chooses to focus on CHCs, not only for their demonstrated appearance but also for the environmental concern accompanied with these compounds. Once in the groundwater, CHCs can degrade the quality of water supplies and cause serious threat to biologic communities. An important feature of this group of compounds is their ability to accumulate in the fatty tissues of organisms (Ayres and Ayres 1999, Ricardi 1991, Carson 1962).

This trait then allows CHCs to migrate, in continuously increasing concentrations, up the food chain. In addition to CHCs, three metals were analyzed. These included mercury, zinc and lead. The metals were chosen based on the same criteria as the CHCs. These metals, if present in high enough concentrations, can disrupt biological processes. It was important to use both CHCs and metals in order to explain solute transport. CHCs will disperse by two processes, namely diffusion and advection (dissolved solids carried with the flowing groundwater). Metals, however, only disperse by advection. By comparing the plumes of CHCs and metals, conclusions can be formulated about dispersion patterns as well as the importance of groundwater flow in mass transport.

Table 2 Monitoring wells used for groundwater samples. All measurements in feet. Based on 2003 data.

Well Name	Depth of Well	Screened Interval	TOC ⁽¹⁾ Elevation	Depth ⁽²⁾ to Groundwater	Elevation ⁽³⁾ Groundwater
GWA-1	90	79-89	454.92	89.45	365.47
GWA-2	95	83.8-93.8	456.56	93	363.56
GWC-1	55	42.3-52.3	415.38	47.59	367.79
GWC-2	41	30.2-40.2	402.62	34.86	367.76
GWC-3	65	53-63	418.97	58.5	360.47
GWC-4	72.5	61.5-71.5	427.27	68.73	358.54
GWC-5	80	71.5-81.5	441.01	78.17	362.84
GWC-6	65	54.5-64.4	429.54	63.02	366.52
P-1	85.9	78.6-88.6	444.93	77.63	367.3
P-2	98.9	91.9-101.9	460.27	95.66	364.61
P-3	98.3	90.6-100.6	458.26	92.73	365.53
P-4	83.8	86.2-96.2	458.13	92.4	356.73
P-5	47.7	40-50	403.28	38.23	365.05
P-7	63.2	55.5-65.5	410.75	53.47	357.28
P-8	44	36-46	403.62	43.82	359.8
P-10	89.1	81.3-91.3	453.95	89.8	364.15

(1) Measured from top of casing

(2) Measured from ground surface

(3) Elevation above mean sea level

An initial effort in assessing water quality in a groundwater basin often includes delineating a three-dimensional contaminant area, using data collected from groundwater monitoring wells. While monitoring wells often produce reliable data in a horizontal plane, a limitation exists when trying to estimate vertical distribution. Monitoring wells in the same area are often screened at about the same depth. This is the case at FTBN-027. Therefore, the groundwater drawn from the aquifer does not show vertical

differences. In order to investigate vertical groundwater quality one must use monitoring wells with large or multiple perforated intervals, as suggested by Collar and Mock (1997).

Lyngkilde and Christensen showed that VOCs often show a decline with a relatively short distance from the landfill (1992). This attenuation, as explained by Eganhouse et al., can result from a combination of processes; including physical, chemical, and biological (2001). Knowledge of which of these processes govern at a given site is important for understanding the fate of any contaminant plume. In order to effectively identify and evaluate the importance of each process the use of tracers is essential. Since the possibility of such a treatment is not available at the study area due to liability concerns from the government agency, the evaluation of the attenuation will therefore only reflect information collected from monitoring wells as found in the groundwater monitoring reports.

Groundwater and Contaminant Model

A calibrated flow model was necessary to effectively simulate groundwater flow and to evaluate contaminant transport at the study site. The three-dimensional flow and transport model was constructed using Visual MODFLOW 2.8.2 accompanied with transport agent MT3D. The first step in applying MODFLOW to the region was to delineate the area to be modeled. While the focus area was the 1st Division Road landfill located in the Harmony Church area at Fort Benning, the aquifer underlying this area extends well beyond the perimeters of the landfill. Therefore, the model had to cover a

large enough area so it could be bounded by natural no-flow structures. Rivers to the east, north and west of the landfill were chosen as model boundaries (Figure 12).

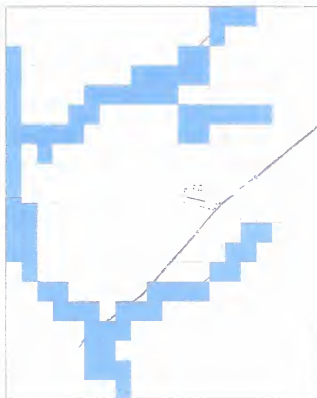
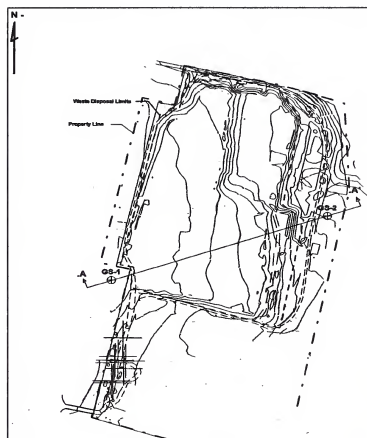


Figure 12 River systems chosen as model boundaries.

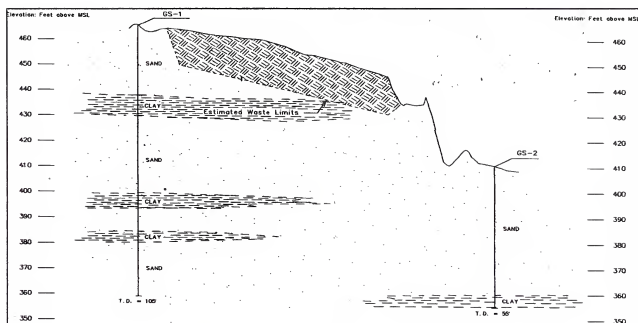
No natural boundary exists south of the landfill; hence no boundary condition was assigned for this area of the model. MODFLOW will therefore automatically assume the edge of the model as being a no-flow boundary. Even though this is not absolutely accurate, it will not bear an important role for the overall accuracy of the model. Since the regional groundwater flow will ultimately end up in the Upatoi Creek, located north of the landfill, and the focus of this research is to describe the contaminant plume

immediately adjacent to the landfill, the hydrogeologic environments south of the landfill will consequently have little effect on the groundwater flow pattern.

A review of the geological settings of the study area indicates that the Eutaw Formation acts as an aquitard. For that reason, this research focused on the conditions present in the Blufftown Formation and assigned the Eutaw Formation as a lower boundary to the aquifer. Consequently, a two-layered model was used to represent the study area. In addition, the geology of the area supports numerous horizontal clay lenses located throughout the Blufftown. Subsurface drill logs indicated that three distinct discontinuous lenses are found underneath the 1st Division Road landfill (Polyengineering Inc. 1995b). A subsurface drill log as well as a subsurface profile are included in Appendix C and Figure 13 respectively. This led to that the model included up to 8 layers at certain areas (Figure 14).



A



B

Figure 13 (A) Index map showing location of geologic cross-section. (B) Geologic cross-section showing subsurface profile A-A'. Modified from Polyengineering Inc. (1995b).

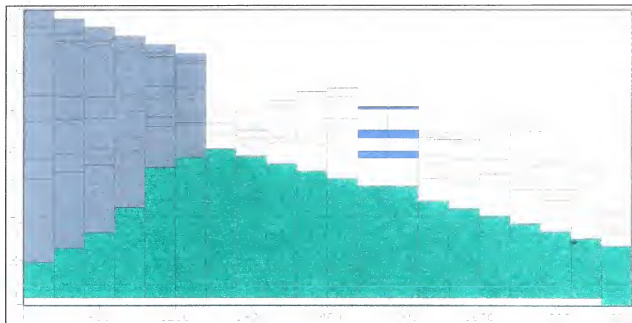


Figure 14 Cross-sectional view for row 10. Picture shows clay lenses (blue), Blufftown (white), Eutaw (green) and inactive cells (gray). All values in meters.

The model domain dimensions contained 20 columns and 20 rows, resulting in 400 cells for each of the vertical layers. This led to that each model cell had a dimension of 335 times 240 meters. The total modeled region contained an area of 80400 m². Figure 15 shows the modeled area and the grid.

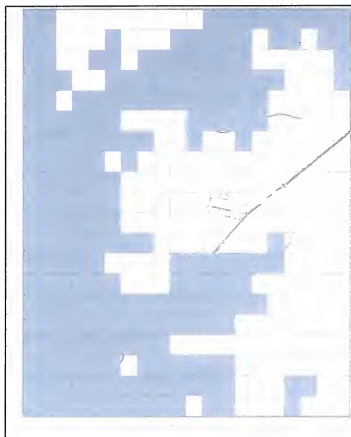


Figure 15 Modeled area and grid. Dark cells indicate inactive areas. All values in meters.

Groundwater flow modeling can be broken down into three major steps: (1) converting a real world setting into a conceptual model, (2) converting a conceptual model into a mathematical model, and (3) solving the mathematical model. Each step has the potential to introduce errors. Moreover, numeric models approximate the conceptual model and the boundary conditions as well as the governing differential equation (Haitjema et al. 2001). The contaminant transport model generated in this research used velocity fields derived from the MODFLOW groundwater model. Consequently, the accuracy of the groundwater model greatly affects the output of the transport model.

Even with high quality, reliable information, data are still insufficient to generate a high resolution model (Gelinis 1996). The subsurface is not a uniform unit. Hydrogeologic properties vary, not only in regards to distance and depth, but also in regards to time. Therefore, core samples and water samples from wells will only indicate conditions at a given point. The data used for calibrating the groundwater model came from monitoring wells scattered throughout the area of the landfill. Sampling events dating back to 1996 for 1st Division Road landfill have established a known groundwater flow pattern in the vicinity of the landfill. Furthermore, hydraulic conductivity as well as porosity values were obtained from slug tests using the same wells (Table 3). However, these monitoring wells are present in close proximity to the landfill and additional monitoring wells east, north and west of the study site are unavailable. Thus the hydrogeologic properties used for this model represent a very small area of the model domain.

Table 3 Hydraulic parameters of the model

Description of Layer	Kx (cm/s)	Ky (cm/s)	Kz (cm/s)	Ss (1/cm)	Sy	Effective Porosity	Total Porosity
Aquifer	4.90E-05	4.90E-05	4.90E-05	0	0.27	0.4	0.4
Clay lenses	5.67E-06	5.67E-06	5.67E-06	0	0.07	0.13	0.13
Aquitard	1.70E-05	1.70E-05	1.70E-05	0	0.07	0.13	0.13

Kx: Hydraulic Conductivity in x

Ky: Hydraulic Conductivity in y

Kz: Hydraulic Conductivity in z

Ss: Specific Storage

Sy: Specific Yield

The assumption is made that the model area is homogeneous and isotropic. Knowing that the project area hosts several thin clay lenses and that these could influence groundwater flow as well as contaminant transport, the assumption is not completely accurate. However, since the clay lenses are not continuous and only occur periodically, their influence on the regional groundwater flow pattern is limited.

RESULTS AND DISCUSSION

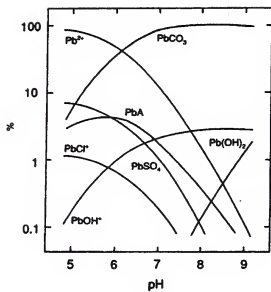
The concentration of different species of trace elements in groundwater is interrelated to chemical processes as well as the intensity of mixing of water with different origin. One of the most important hydrochemical parameter that influences the fate of metals in groundwater is pH (Salbu and Steinnes 1995). Most groundwater systems show pH values ranging from 5.0 to 8.0 (Walton 1970). The chemical water analyses from the study area indicate pH values at the lower level of this range. Monitoring reports suggest that the pH fluctuate between 3.8 and 6.6, with the majority of the readings around 4.2. These relatively low pH values can be explained by small amounts of organic acids, which are products resulting from the breakdown of organic compounds. It is possible to predict the abundance of metal species knowing the pH.

Lead: The precipitation equilibrium and the complexes it forms with inorganic and organic ligands determine the behavior of lead in groundwater. The degree of mobility of lead depends on the physicochemical state it is in (Moore and Ramamoorthy 1984). As discussed in the previous section, the fate of lead is highly determined by the pH. Hydrolysis is a significant process at $\text{pH} > 6$ (Figure 16a). However, rather than the hydrolysis products being the most dominant at this pH, PbCO_3 is expected to be the most abundant species in solution. At lower pH ($\text{pH} < 6$), the Pb^{2+} ion dominates.

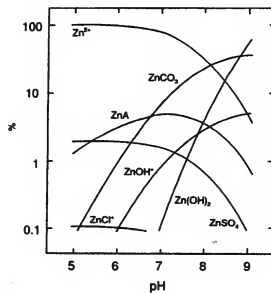
Zinc: The free Zn^{2+} ion is the most common species of zinc at $\text{pH} < 8$ (Figure 16b). In this form, zinc is available for sorption with mineral colloids and binding with organic matter. The sulfate complex ZnSO_4 can be present in groundwater at significant levels at low pH and high sulfate concentrations. It can be assumed that the zinc-sulfate

complex is not an abundant species at this site due to the low sulfate concentrations in the soil.

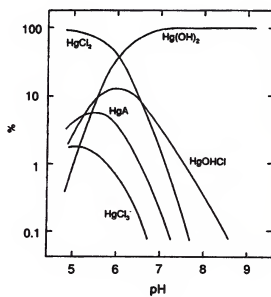
Mercury: The elemental state of mercury will dominate in most natural waters. Mercury forms strong complexes with oxygen, chloride and sulfur. The chloride complexes HgCl_2 and HgCl^+ are more abundant at $\text{pH} < 5$ compared to hydroxide species (Figure 16c). Significant hydrolysis starts at $\text{pH} > 1$ and dominates at $\text{pH} > 2$, in the absence of other complexing agents.



a



b



c

Figure 16 (a) to (c) Distribution of metal species (Pb, Zn and Hg) in solution vs. pH in groundwater. Source: Salbu and Steinnes (1995).

The chemical composition of the groundwater is derived from constituents that can occur in both dissolved ($<0.45\mu$) and suspended phase (colloids and other particulates). Since the samples from the background sampling report produced by CESAS were unfiltered, the concentrations reported for these analytes could occur in either phase. According to this report, neither mercury nor lead was detected in any groundwater samples from the Blufftown Formation and the Eutaw Formation. Zinc was detected in four samples from the Blufftown Formation and in one sample from the Eutaw Formation. The mean was 0.034 mg/L. Although zinc was detected, the low concentrations and the relative infrequency of detect-samples indicates that zinc exist in a stable form. Table 4 and 5 show groundwater statistical summations for metals in the Blufftown Formation and the Eutaw Formation. These data could support two explanations. The first one is that the metals included in this research were not present, or present in very low concentrations with very low solubility before the landfill became active. Another explanation is that the metals were present in significant amounts but did not display a high mobility pattern and would therefore not be detected in sampling events. This is, however, unlikely as acidic environments allow metals to stay more soluble which would increase the mobility of the metal species. It can therefore be concluded that the metal concentrations reported in groundwater monitoring reports results from the leachate associated with the 1st Division Road landfill.

Table 4 Blufftown background groundwater statistical summation

Analytes	Number of Samples	Number of Non-Detects	Percent of Data Non-Detects	Mean (mg/L)	Minimum	Maximum	Type of Distribution (*)
Lead	10	10	100	0.013	ND	ND	F
Mercury	10	10	100	0.500	ND	ND	N
Zinc	10	6	60	0.034	ND	0.070	F

(*) N = normal distribution, F = neither normal nor log normal distribution

Table 5 Eutaw background groundwater statistical summation

Analytes	Number of Samples	Number of Non-Detects	Percent of Data Non-Detects	Mean (mg/L)	Minimum	Maximum	Type of Distribution (*)
Lead	12	12	100	0.011	ND	ND	F
Mercury	12	12	100	0.500	ND	ND	N
Zinc	12	11	91.67	0.053	ND	0.070	F

(*) N = normal distribution, F = neither normal nor log normal distribution

It has been suggested that mobile colloids could act as primary vectors in contaminant transport (Buddemeier and Hunt 1988). The large surface area of colloids allows for many reactions at the solution-particle interface. This is a determining factor in controlling both the migration of a substance as well as the fixation of elements (Krauskopf and Bird 1995). McDowell-Boyer et al. suggested that charged colloids could play an important role in facilitated transport of metals (1986). Whereas extensive data exists on uncharged colloid transport through various media, there has been limited research conducted on charged colloid transport. In order to support colloidal facilitated

transport, three conditions must be met (Ryan and Elimelech 1996). First, colloids must be present in the groundwater system. Second, contaminants must associate with the colloids and third, evidence of colloid-contaminant combinations moving through the groundwater system must be present. The results of this research meet all three of these conditions, as discussed below. It is however important to keep in mind that since the groundwater monitoring plan designed for FTBN-027 did not include testing for colloids. Therefore, the discussion presented here is based on assumptions and not supported qualitatively as no data was collected.

It can be assumed that most of the metal transport at the study site occurs in the form of colloids. Since lead, zinc and mercury all exist in elementary form (as shown earlier); they easily form strong bonds with many natural organic ligands. The distribution pattern of these elements found by this research indicates that the mobility has dramatically increased after operation of FTBN-027 started. When examining the contamination plume, the leachate includes elevated levels of organic compounds. This would meet the first requirement, supporting the idea that colloids are present. It can be presumed that the organic substances in the leachate promote the mobility of metals by functioning as transport agents. This bonding of metals to organic substances would be highly likely at the study site since all investigated metals exist in their elemental states that would form bonds with organic substances. Therefore, metal-colloid combinations will likely exist in high quantities. As discussed earlier, evidence is present that the concentration levels of metals have increased as a result of the land use. This indicates that the mobility of metals has improved. This would then support the third

condition. It can therefore be concluded that colloids account for the most significant process by which metals are transported at the study site.

Bacteria decompose landfill waste in four phases (Figure 17). The composition of the gas produced changes with each of the four phases of decomposition. Different areas (cells) of the landfill can be in different phases of decomposition at the same time depending on their depth, with the oldest debris being at the bottom. A landfill can thus undergo several phases of decomposition at once. The 1st Division Road landfill operated for 13 years between 1985 and 1998. The waste in the landfill ranges in age from 8 to 20 years. The waste placed in the landfill in the 1980s would be in a later phase of decomposition than waste placed much later. It is therefore likely that older waste in one area of the landfill experience different decomposition processes than more recently buried waste in another area.

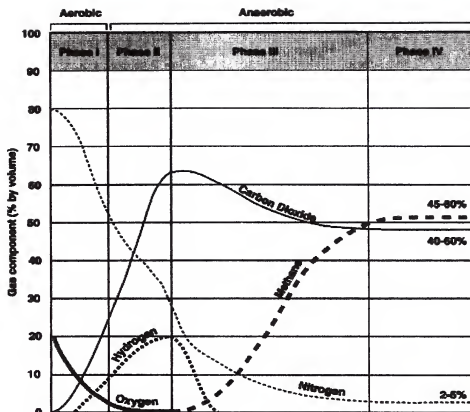


Figure 17 The composition of the gas produced during each of the four phases of decomposition. Phase duration times varies with landfill conditions. Source: U.S. EPA (1997).

Phase 1 of decomposition is characterized by the break down of long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. A decrease in oxygen occurs as aerobic bacteria breaks down organic-type waste. Phase 1 continues until available oxygen is depleted.

The second phase begins when all the oxygen has been exhausted. Anaerobic bacteria are dominant during this phase and they further breakdown byproducts of phase 1 onto a variety of acidic compounds and alcohols such as methanol and ethanol. Landfill leachate gradually becomes more acidic during this phase. This process is completely anaerobic.

The beginning of phase 3 occurs when certain species of anaerobic bacteria consume the organic acids produced during phase two. A common waste byproduct of this metabolic process is acetate. As acids are consumed the landfill leachate rises in pH to neutral creating a favorable environment for methane producing bacteria. Methane- and acid-producing bacteria have a symbiotic relationship. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume certain compounds that, in high enough concentrations, would be toxic to the acid-producing bacteria.

Phase 4 is relatively stable and begins when both the composition and production rates of landfill gas remain somewhat constant. The gas usually contains approximately 45% to 60% methane by volume, 40% to 60% carbon dioxide, and 2% to 9% other gases, such as sulfides. This phase typically produces gas for about 20 years; however, gas will continue to be emitted in small quantities for 50 or more years after the waste is placed in the landfill (ATSDR 2001).

The gases resulting from degradation processes follow a concentration gradient and move away from sources of generation in all directions. If the gases are lighter than air they will expand and migrate upward through void spaces in the refuse. Landfill gases will also migrate outwards flowing along geological barriers, such as dense rock or clay, that would restrict further downward migration. These barriers can also influence the outward direction of the gasses. A dense clay layer approximately 25 bgs (below ground surface) has influenced landfill gas migration at 1st Division Road landfill, causing the gases to migrate outward impacting the groundwater and nearby structures.

In addition, the impermeable liner that covers the landfill inhibits part of the landfill gases rising to the surface. These gases become concentrated below the surface and migrate horizontally through voids in the waste to other areas within the landfill or continue through permeable sands that lie above the clay layer beyond the landfill footprint. Once outside the landfill, the upward path is resumed. However, the degradation processes also produce gases that are denser than air. These gases will exhibit a different tendency. Rather than migrate upwards, dense gases will collect in subsurface areas. Although the weight of gases can explain some of the observed behavior of landfill gases, migration patterns are more complex and are influenced by a variety of factors. These factors include diffusion rates of different compounds, surface atmospheric pressure and the permeability of the material. Diffusion refers to the movement of a gas down its concentration gradient. Since the gas concentrations are normally higher in a landfill compared to the outside environment, gases diffuse out of the landfill. Gases are also influenced by pressure. Low-pressure areas allow gases to move freely where high-pressure areas cause a restricted movement of gases. As gases are generated and accumulate in the landfill, the pressure increases. This causes convection, the movement of gases from a high-pressure zone to an area with lower pressure. Gases follow the path of least resistance. The permeability influences how easy gases migrate through connected pore spaces in soils and waste material. Therefore, gases tend to move through areas of high permeability rather than through areas of low permeability.

These gases, as they move through the landfill, will affect the migration pattern of CHCs. It is highly unlikely that landfill produced gases will interact with waste material and degraded compounds, as this would require a lot of energy and pressure. However, rather than chemically interact with the waste; the gases will cause migration of volatiles in the landfill by exposing them to pressure. It is therefore easy to see that volatiles will constantly move inside the landfill. The pressure will allow CHCs to move both vertically and horizontally within the landfill. The pressure asserted by the gases will not only trigger CHCs to move from one area to another within the landfill, it will also affect the release of leachate from the landfill. As pressure increases at various compartments in the landfill, leachate will be forced out. However, this movement is far from constant as the gas composition as well as the pressure levels vary throughout the landfill. The result is that landfill gases and leachate move in a pulse-like fashion. If indeed this occurs at the study site, the concentration levels for all the investigated CHCs should then vary over time. The plotted concentration curves for the volatile compounds studied for this research show a highly irregular pattern (Appendix D). The concept of landfill gases and leachate moving in pulsing waves as concentration levels increase and decrease helps support the varying concentrations of CHCs over time.

Other factors beside gas composition and pressure affect leachate movement within and outside the landfill. Solid waste landfills are extremely complex and heterogeneous environments. The decaying rate of the waste is far from constant and is influenced by a number of factors, including the landfills moisture content, waste composition and biodegradability, the waste's physical state and temperature. Arguably,

the most important environmental factor influencing biodegradation processes is solid waste moisture content. The geotextile and clay cap that was placed on the 1st Division Road landfill after closure has prevented the influx of water. However, until the landfill was closed, it was uncapped and thus exposed to the elements of the environment. Water during this time period would infiltrate the landfill during rain events. Some of this water is still present within the landfill having been absorbed by the contents of the landfill (paper, fabrics, furniture, etc.). As the waste decays, the landfill settles and as the materials shift, water is released, further aiding the degradation processes. Settling also creates new pockets to hold water and move water along with new voids that change the flow of gases. The moisture content in different parts of the landfill will therefore vary over time. The degradation rate will consequently fluctuate over the entire area of the landfill.

A two-layered finite-difference flow model was used to simulate the groundwater flow pattern in the uppermost aquifer beneath the 1st Division Road Sanitary landfill. Simulations were run under a steady-state condition. The simulated result indicated that the study area has both local and regional groundwater flow systems. A difference in flow direction between the two flow systems is present. The area directly underneath the landfill hosts a local flow system with a direction north to south as indicated by potentiometric maps. Local groundwater flow systems often form in humid regions and have recharge areas at topographic high spots (Fetter 2001). Regional flow systems are not influenced by local recharge areas. Instead, these systems depend on the basin-shape geometry. The discharge area constitutes valley bottoms. For the modeled area, Upatoi

Creek north of the landfill is a major river system and acts as the largest flow system. Consequently, this body of water has the greatest impact on the regional flow pattern. As a result, the regional flow direction is generally towards the north (Figure 18). Figure 19 shows a cross-sectional segment indicating the water table as well as the regional flow system in the Eutaw Formation.



Figure 18 Regional groundwater flow. Green arrows indicate in plane flow while red arrows indicate out of plane flow. All values in meters.

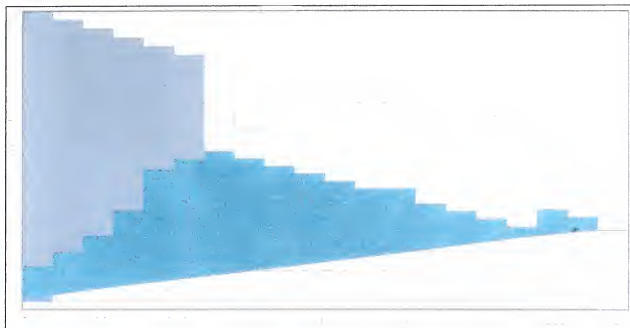


Figure 19 Cross-section for row 10. Figure shows the water table and the regional groundwater flow towards Upatoi Creek (north). Gray area indicates inactive cells. All values in meters.

The release of contaminants from the 1st Division Road Sanitary landfill was modeled using the transport agent MT3D based on the distribution of selected CHCs and metals. Significant downward migration occurred through the Blufftown Formation for both CHCs as well as metals. Figure 20 shows a cross-section of the groundwater flow direction for the upper portion of the Blufftown Formation.



Figure 20 Cross-section showing the groundwater flow direction directly beneath 1st Division Road landfill.

The migration changed direction to a more horizontal movement when the contaminants reached the Eutaw Formation and the water table. As a result, a leachate plume is spreading from the landfill both vertically and horizontally. The MT3D model was run for 25 years. The distributions as well as the concentrations of the plumes were observed after 5, 10 and 25 years. In addition, metal distribution was also simulated for 150 years due to the low concentrations and the slow migration pattern. The total concentrations for the selected CHCs and the metals were calculated by adding all the readings from one sampling event and take the average. CHCs and metals were treated independently. The sampling event of July 1998 was chosen for its consistency to provide data. The resulting plumes over time for the CHCs and the metals are shown in Figures 21-27. As expected, CHCs as well as metals showed a dominating vertical movement through the Blufftown

Formation. However, Figures 21-23 also indicates that CHCs migrate out horizontally from the landfill. This is due to the process of dispersion.

Test borings from the study area indicated that the subsurface soils are mainly sands with occasional clay layers. A Cation Exchange Capacity (CEC) was conducted by Polyengineering Inc. during the hydrogeologic site assessment in 1995. CEC is a measurement of the soils' attenuation capability. The results showed that the attenuation capacity was very low. Due to the relatively high rate of percolation of leachate through the soils between the base of the landfill and the water table, biological attenuation can be assumed to be low (Polyengineering Inc. 1995b). As a result, a potential for groundwater pollution exists. However, according to Geosciences, the groundwater flow velocity for the uppermost aquifer at the site ranged from 0.04 ft/day at minimum hydraulic conductivity, minimum gradient to 0.22 ft/day at maximum hydraulic conductivity, maximum gradient. Based on these flow velocities, the anticipated travel time from the site to the nearest body of water (creek east of landfill) would be approximately 19 to 102 years (Polyengineering Inc. 1995b). However, the mathematical model indicates a groundwater flow direction which makes Upatoi Creek the most likely receptor, located more than 1.5 miles north of the study site. Due to dilution, dispersion and retardation, no detectable pollutants are expected to reach surface streams.

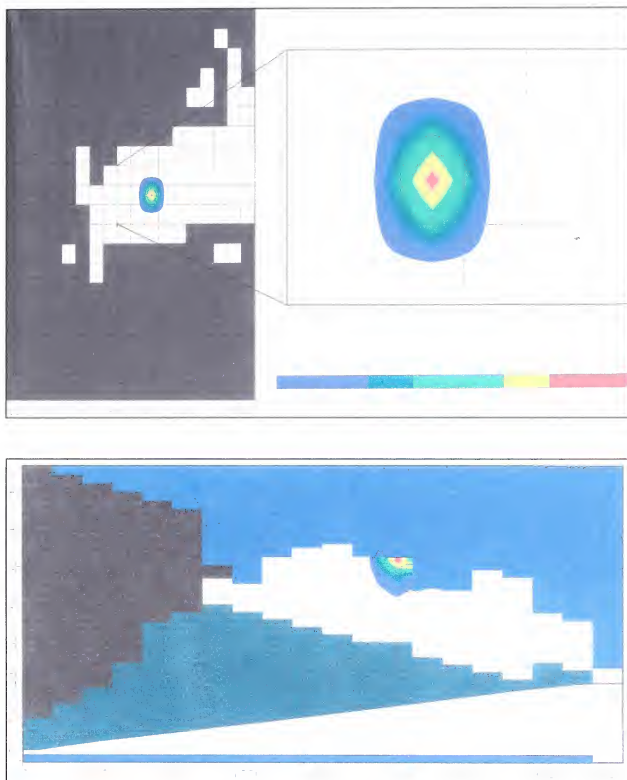


Figure 21 Leachate plume of CHCs after 5 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in mg/L.

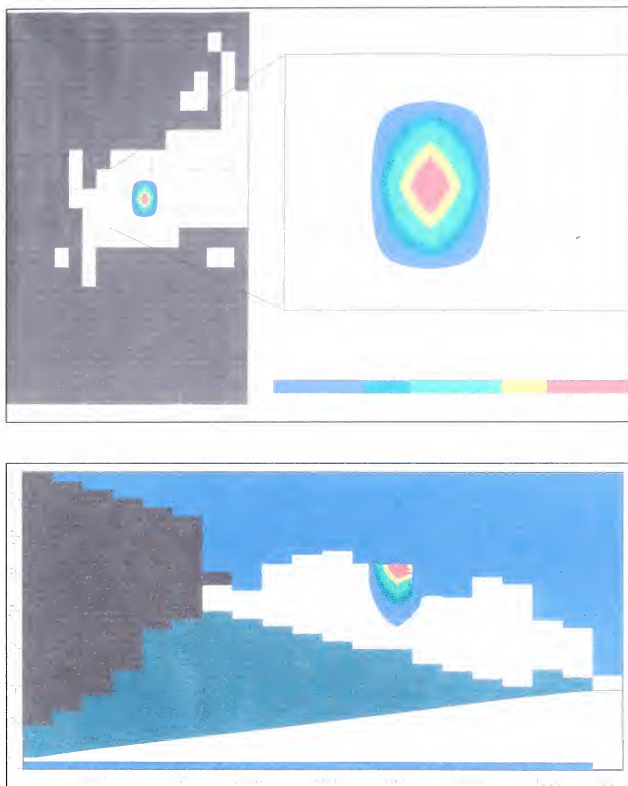


Figure 22 Leachate plume of CHCs after 10 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in mg/L.

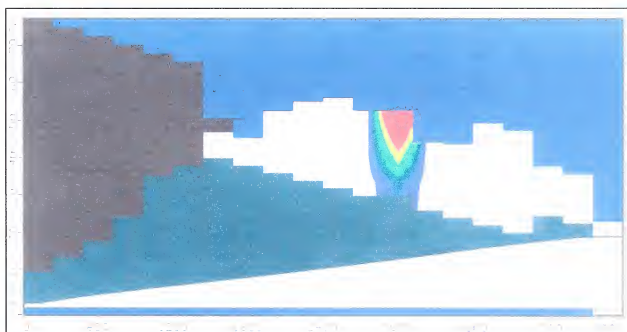
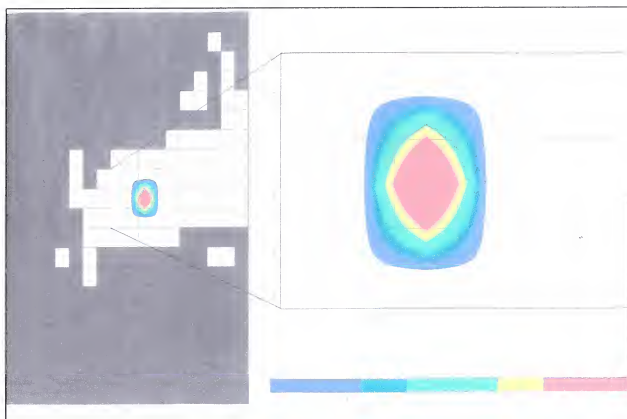


Figure 23 Leachate plume of CHCs after 25 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in mg/L.

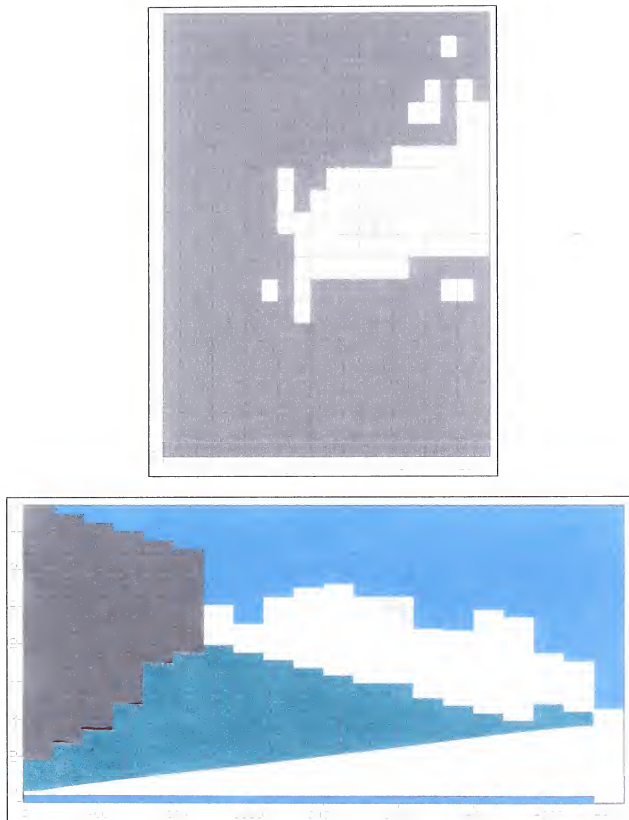


Figure 24 Leachate plume of metals after 5 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in ug/L.

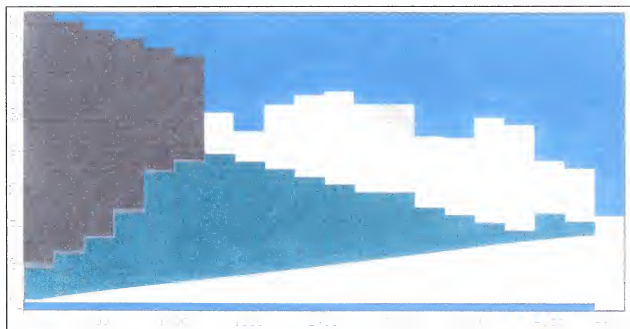
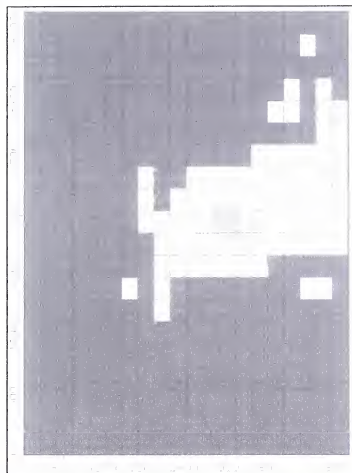


Figure 25 Leachate plume of metals after 10 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in ug/L.

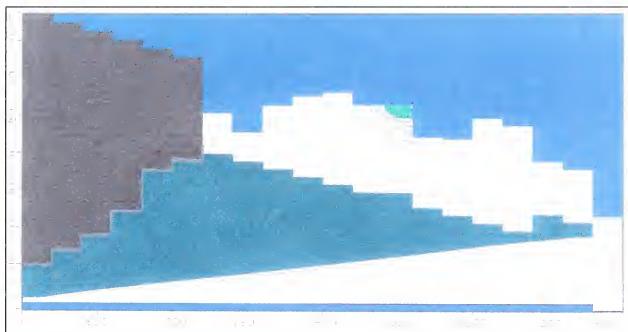
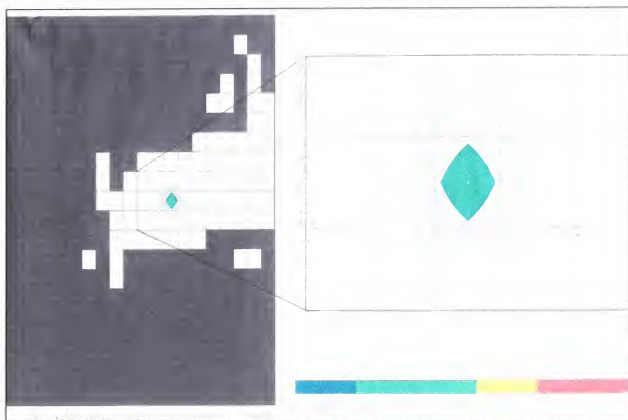


Figure 26 Leachate plume of metals after 25 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in ug/L.

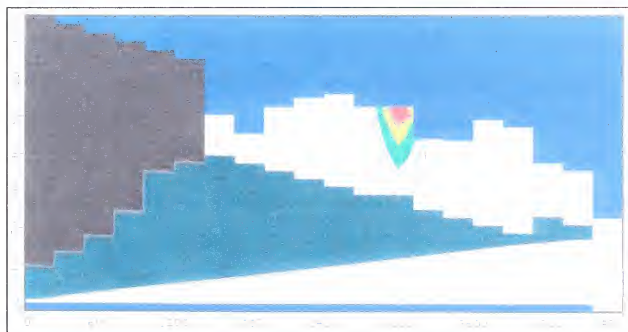
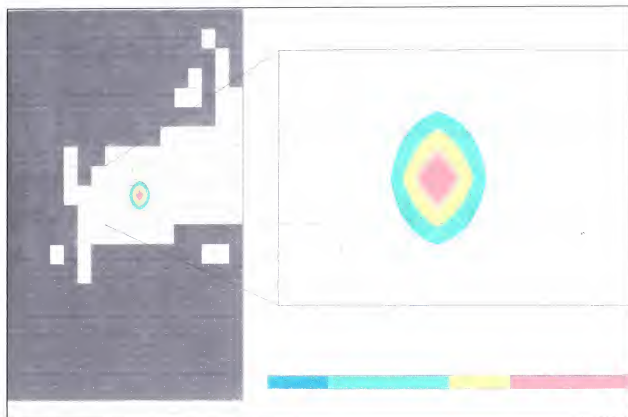


Figure 27 Leachate plume of metals after 150 years. Upper image shows horizontal distribution while the lower image indicates vertical distribution. Concentrations measured in $\mu\text{g/L}$.

CONCLUSION

Concentration of selected CHCs and metals were shown to identify the leachate plume emerging from 1st Division Road Sanitary landfill at Fort Benning, Georgia. Groundwater samples from monitoring wells around the study area show elevated concentrations of target compounds compared to background samples, with many readings above MCLs. The sources of the CHCs and the metals are diverse, reflecting the wide range of anthropogenic, natural and military materials that have historically been placed in the landfill. Concentrations of both CHCs and metals show a highly irregular pattern over time. Groundwater does not continuously flow through the landfill. Instead, water movement through the landfill is mainly caused by recharge from precipitation. This suggests that leachates disperse from the landfill as discrete pulses rather than as a continuous plume. In addition, the variety in composition of disposed material as well as the difference in time of disposal will also affect the production of leachate. These relationships help explain the irregular concentrations levels.

The MODFLOW model designed for the study area was a two-layered, heterogeneous and isotropic model. Based on borings installed in the project area, thin clay lenses exist throughout the Blufftown Formation and could influence contaminant migration. Hydraulic conductivity values used in model calibration were established using rising-head slug tests, which represent a very small area of the project site. Modeling contaminant transport for predictive analysis as well as plume stability required input of concentrations for both CHCs and metals over a given area and injected over a given amount of time. As the release time and amount leached from the landfill was

highly irregular, values were estimated based on data gathered at the site. The model indicated that migration for both CHCs and metals were caused by advective transport. In addition, the simulated result also indicated that CHCs migrated by the process of diffusion. More pumping and slug test data are required for a more precise model. The generated groundwater and transport model indicates that contaminants mainly will migrate towards the north with the regional groundwater flow. Potentiometric maps produced over the years for the study site show the local groundwater flow direction to be toward the southeast. As a result, the existing groundwater monitoring network emphasizes well locations south of the landfill. Moreover, monitoring wells are today located in close proximity to the landfill and screened within the same depth. Wells need to be added to compensate for this. An expansion of the existing groundwater monitoring system is therefore proposed. Additional wells must be drilled north of the landfill to better monitor leachate migration. Furthermore, in order to account for the regional groundwater flow, deeper wells need to be installed. Also, for a more complete picture of the contaminant transport processes at work at the study site, the use of tracers is recommended.

Groundwater flow velocities and the distances from the landfill to potential surface receptors indicate that it is not likely that landfill-derived contaminants would be detected in streams. However, this investigation did not analyze surface streams for the presence of contaminants. It is therefore recommended that periodic tests for leachate in Upatoi Creek and Ochillee Creek are conducted.

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APPENDIX A: Subsurface drill log of Chattahoochee CO #1. Source: Marsalis and Fridell (1975).

Coring run	Recovery	Description
BLUFFTOWN		
0'- 15'	Washed	Sand, pale yellowish orange (10YR6/6) to moderate reddish orange (10R6/6) to pale purple red (5RP6/2), medium to coarse grained, quartzose, subangular, silty
23'- 26'	3'09"	0-2' — Sand, light brown (5YR5/6), fine to coarse grained, quartzose, subangular, silty, slightly micaceous 2'-3'9" — Silt and very fine grained quartzose sand, dark yellowish orange (10YR6/6) to light gray (N7) to dusky red (5R3/4), subangular, micaceous
26'- 28'	3'00"	0-10" — Sand, light brown (5YR 5/6), fine to coarse grained, quartzose, subangular, slightly micaceous 10"-2'5.5" — Silty clay to clayey silt, dark yellowish orange (10YR6/6) to light gray (N7), slightly sandy, micaceous 2'5.5"-3' — Sand, grayish orange (10YR7/4), coarse to occasional very coarse grained, quartzose, subangular, slightly micaceous.
28'- 30'	1'7"	0-1'7" — Sand, grayish orange (10YR 7/4) to dark yellowish orange (10YR6/6) to very pale orange (10YR8/2), very fine to medium grained, quartzose, subangular, silty
30'- 42'	3'03"	0-10" — Sand, pale yellowish orange (10YR8/6), fine to coarse grained, quartzose, subangular, silty 10"-2'11" — Silt and very fine grained quartzose sand, dark yellowish orange (5P4/2). Sand is subangular, slightly clayey, micaceous 2'11"-3'3" — Sand, dark yellowish orange (10YR6/6), medium to coarse grained, quartzose, subangular, silty
42'- 51'	1'06"	0-1'6" — Sand, dark yellowish orange (10YR6/6), medium to coarse grained, quartzose, subangular, silty
51'- 60'	1'06"	0-4'11.5" — Sand, dark yellowish orange (10YR6/6) to very pale orange (10YR8/2) to grayish red purple (5RP4/2), very fine to medium grained, quartzose, subangular, slightly silty. The lower 3'5.5" of this unit contains some coarse grains.
60'- 68'	3'02"	
68'- 70'	0'03.5"	
70'- 75'	2'11"	0-11" — Sand, dark yellowish orange (10YR6/6) to very pale orange (10YR8/2) to grayish red purple (5RP4/2), fine to medium grained (occasional coarse grains), quartzose, subangular, micaceous.
EUTAW		
		11"-2'11" — Sand, dark yellowish orange (10YR6/6) to white (N9), very fine grained, quartzose, subangular, silty, micaceous
75'- 84'	6'03.5"	0-2'9" — Sand, dark yellowish orange (10YR6/6) to white (N9), very fine grained, quartzose, subangular, silty, micaceous 2'9"-6'3.5" — Sand, light gray (N7), very fine to fine grained, quartzose, subangular, silty, very micaceous, lignitic, grading downward into a clay, olive black (5Y2/1), sandy, silty, micaceous, lignitic.
84'-84'06"	0'06"	0-6" — Clay, olive black (5Y2/1), sandy, silty, micaceous, lignitic

Coring run	Recovered	Description
84'6"- 90'	9'11"	0-7'5" — Clay, grayish black (N2), sandy, silty, slightly micaceous, lignitic; this unit grades downward into: 7'5"-9'11" — Sand, light olive gray (5Y6/1), very fine grained, quartzose, subangular, silty, micaceous, lignitic
90'- 96'	9'04"	0-2'4" — Sand, light olive gray (5Y6/1), very fine grained, quartzose, subangular, silty, micaceous, lignitic. This unit overlies: 2'4"-8'11" — Clay, olive black (5Y2/1), silty, micaceous, lignitic (containing plant fragments). This unit is increasingly sandy with depth, grading into: 8'11"-9'4" — Sand, medium dark gray (N4), very fine grained, quartzose, subangular, very clayey, silty, very micaceous, lignitic
96'-101'	8'07"	0-4'05" — Sand, medium gray (N5), very fine grained, quartzose, subangular, very micaceous, lignitic. This unit grades downward into: 4'5"-6' — Clay, dark gray (N3), slightly sand. This unit overlies: 6'-8'07" — Sand, moderate greenish gray (5GY7/1), very fine grained, quartzose, subangular
101'-102'	1'02"	0-11" — Sand, light gray (N7), very fine grained, quartzose, subangular, silty, micaceous, slightly lignitic; clayey portions of this sand contain casts and molds of mollusks. 11"-1'2" — Clay, olive gray (5Y4/1), fissile, sandy, micaceous, carbonaceous; contains mollusk casts and molds
102'-105.5'	9'07"	0-9'7" — Sandy silty clay to clayey silty sand, dark gray (N3), micaceous, contains occasional mollusk casts and molds. This unit becomes increasingly sandy and micaceous downward
105.5'-110'	10'00"	0-1' — Clay, olive gray (5Y4/1), very sandy, micaceous, lignitic 1'1"-2'10" — Sand, yellowish light olive gray (5Y7/1), very fine grained, quartzose, subangular, silty, micaceous, lignitic. This unit grades downward into: 2'10"-8' — Sand, medium light olive gray (5Y5/1), very fine grained, quartzose, subangular, clayey, silty, micaceous, carbonaceous. This unit grades into: 8'-10' — Clay, olive black (5Y2/1) to grayish black (N2), silty, slightly sandy, slightly micaceous
110'-115'	9'08"	0-3'6" — Clay, olive black (5Y2/1) to grayish black (N2), silty, slightly sandy, slightly micaceous 3'06"-4'3" — Silty quartzose sand to sandy silt, greenish gray (5GY6/1); sands are very fine grained, subangular, micaceous, lignitic 4'3"-7'5" — Clay, olive gray (5Y4/1) to olive black (5Y2/1), sandy, silty, micaceous, lignitic, fossiliferous. Contains some casts and molds 7'5"-9'8" — Sand, olive gray (5Y4/1) to light olive gray (5Y6/1), very fine grained, quartzose, subangular, micaceous, slightly lignitic
115'-118'	5'09"	0-5'9" — Sand, olive gray (5Y4/1) to light olive gray (5Y6/1), very fine grained, quartzose, subangular, micaceous, slightly lignitic
118'-121'	4'02"	0-4'2" — Clay, olive black (5Y2/1), fissile, sandy, silty, lignitic

Coring run	Recovered	Description
121'-129'	9'09"	0-4" — Clay, olive black (5Y2/1), fissile, sandy, silty, lignitic 4"-5' — Clay, same as above except it is less fissile and more sandy, grading downward (beginning at approximately 3'11") into a sandy clay to sandy silt, olive gray (5Y4/1) to greenish black (5G2/1) to grayish black (N2), micaceous, lignitic 5'-9'09" — Sand and silt, very light olive gray (5Y6/1), very fine grained, quartzose, subangular, clayey, silty, micaceous, lignitic, some questionable borings
129'-131'	2'02"	0-2'02" — Quartzose, very fine grained sand to silt, very light gray (N8) to light olive gray (5Y6/1), subangular, micaceous, lignitic, calcareous (shell fragments). In the lower 9", this unit is a clayey sandy silt, dark olive gray (5Y3/1), micaceous, lignitic, slightly calcareous
131'-142'	2'08"	0-9" — Clay, dark olive gray (5Y3/1), fissile, silty, micaceous, slightly calcareous 9"-2'8" — Sand, very light gray (N8), very fine grained, quartzose, subangular, slightly silty, micaceous slight lignitic
142'-146'	5'	0-2'9" — Sand, very light gray (N8), very fine grained, quartzose, subangular, slightly silty, micaceous, slightly lignitic 2'9"-5' — Sand, light gray (N7) to very light gray (N8), very fine grained, quartzose, subangular, silty, slightly micaceous. In the upper 2.5", this unit is fossiliferous, calcareous (calcareous shell fragments)
146'-150'	4'05"	0-9'9" — Sand, yellowish light olive gray (5Y7/1) to very light gray (N8), very fine grained, quartzose, subangular to subrounded, micaceous, fossiliferous (original shell material), lignitic (clayey zones contain plant stems and occasional leaves)
150'-155'	5'04"	
155'-158'	2'03.5"	0-2'3.5" — Sand, medium olive gray (5Y5/1), very fine grained, quartzose, subangular to subrounded, silty, micaceous, slightly lignitic, calcareous, fossiliferous (original shell material). This unit contains occasional very thin layers of clay.
158'-164'	6'08"	0-5" — Sandstone, medium light gray (N6), fine grained, quartzose, indurated, micaceous, calcareous 5"-2'11" — Sand, light olive gray (5Y6/1), very fine grained, quartzose, subangular, silty, lignitic, calcareous, fossiliferous (original shell material) 2'11"-3'8" — Siltstone, medium gray (N5) to medium light gray (N6), indurated, sandy, clayey, calcareous, fossiliferous (original shell material) 3'8"-4'11" — Sand, very light gray (N8), very fine grained, quartzose, subangular, silty, micaceous, calcareous, fossiliferous (original shell material) 4'11"-6'8" — Silt, olive gray (5Y4/1), sandy, clayey, micaceous, lignitic, calcareous, fossiliferous (original shell material). This unit becomes more sandy toward its base, grading into:
164'-165'	10"	Sand, light gray (N7) to olive gray (5Y4/1), very fine grained, quartzose, subangular, silty, micaceous, calcareous, fossiliferous (original shell material)
165'-174'	8'11"	0-5'9" — Sand, light gray (N7) to olive gray (5Y4/1), very fine grained, quartzose, subangular, silty, micaceous, calcareous, fossiliferous (original shell material). Clayey portion occurs from 4'3" to 4'7".

Coring run	Recovered	Description
		5'9"-6'10" — Sandstone, medium light gray (N6), very fine grained, quartzose, indurated, micaceous, calcareous, fossiliferous (contains original shell material, especially in the lower 6"). This unit is separated from the next lower one by a ¼" thick clay, olive gray (5Y4/1), slightly silty, slightly calcareous
		6'10"-7'7" — Silt to silty, very fine, quartzose, sand very light gray (N8), micaceous, calcareous, fossiliferous (some original shell material present), iron-stained. This unit grades downward into:
		7'7"-8'4" — Sandstone, light gray (N7), fine to very fine grained, quartzose, indurated, quite fossiliferous (casts and molds and original shell material)
		8'4"-8'11" — Silt, dark yellowish orange (10YR6/6), sandy, micaceous, carbonaceous, slightly calcareous, sparsely fossiliferous (original shell material)
174'-180'	5'6"	0-5'6" — Sand and silt, light gray (N7) to olive black (5Y2/1); sand is very fine grained, quartzose, subangular to angular, silty, micaceous, carbonaceous. Slightly calcareous in upper 9". This unit is slightly fossiliferous throughout (casts and molds). Original shell material occurs in upper 9".
180'-190'	4'1.5"	0-4'1.5" — Sand, light gray (N7) to light olive gray (5Y6/1), very fine grained, quartzose, silty, (contains occasional coarse to very coarse grains in lower 1'), micaceous, lignitic, slightly fossiliferous (casts and molds). Some pyrite is associated with the lignite.
190'-195'	2'7"	0-2'7" — Sand, medium dark gray (N4) to light gray (N7), fine to very coarse grained, quartzose, subangular, silty, micaceous, lignitic, pyritiferous, fossiliferous (lignitic plant remains)
195'-201'	1'1"	0-1'1" — Sand, light gray (N7), fine to very coarse grained, quartzose, subangular, slightly silty, feldspathic
201'-207'	6'0"	0-1'3" — Sand, very light gray (N8), coarse grained, quartzose, subangular, micaceous. This unit overlies:

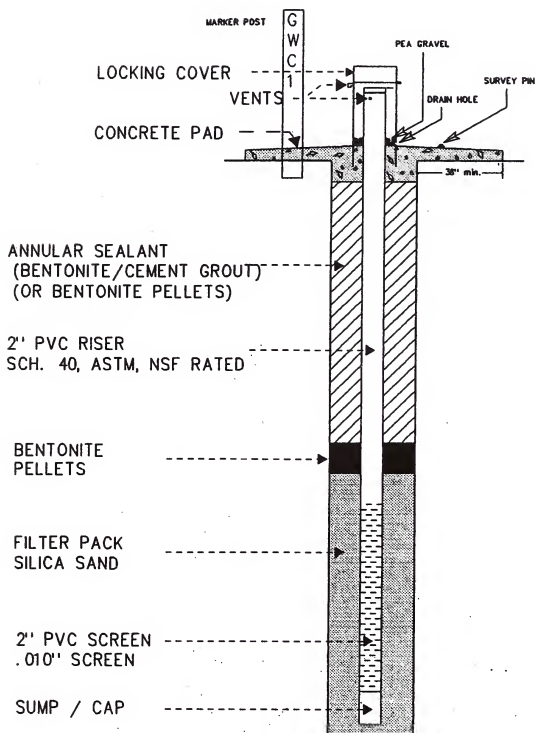
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		1'3"-6' — Clay, light gray (N7), with occasional moderate reddish brown (10R4/6), silty, sandy, slightly micaceous, occasional small crystals of pyrite
207'-210'	2'10"	0-2'10" — Clay, light gray (N7), in places moderate reddish brown (10R4/6), silty, sandy, slightly micaceous, grading downward into a sand, yellowish gray (5Y3/1), very fine grained, quartzose, subangular, silty, micaceous
210'-225'	1'06"	Sand, yellowish gray (5Y8/1), very fine grained, quartzose, subangular, silty, micaceous. In the lower 0.5", this unit is a sand, light gray (N7), coarse to very coarse grained, quartzose, subangular, silty, feldspathic. Lignitic material is present at the contact of these two units.
225'-235'	4'02"	0-0.5" — Sand, light gray (N7), coarse to very coarse grained, quartzose, subangular, silty, feldspathic. This unit overlies: 0.5"-4'2" — Clay, very light gray (N8), slightly sandy, slightly silty, micaceous. This unit grades downward into a sand, very light gray (N8), fine to coarse grained, quartzose, subangular, silty, clayey, micaceous, slightly feldspathic

Coring run	Recovered	Description
235'-236'	10"	0-10" — Sand, very light gray (N8), fine to coarse grained, quartzose, sub-angular, silty, clayey, micaceous, slightly feldspathic
236'-245'	8'11"	0-7'8" — Sand, very light gray (N8), fine to coarse grained, quartzose, sub-angular, silty, clayey, micaceous, slightly feldspathic 7'8"-8'11" — Sand, moderate yellowish olive brown (5Y5.5/6), very fine to medium grained, quartzose, angular to subangular, clayey, micaceous. This unit contains some pea size gravel and small pebbles in lower portion.
245'-255'	7'04"	0-7'4" — Sand, light gray (N7) to grayish red (5R4/2), very fine to medium, quartzose, subangular, clayey, micaceous, feldspathic
255'-257'	2'04"	0-2'4" — Sand, very light gray (N8), fine to coarse grained (in places, very coarse grained), quartzose, angular to subangular, micaceous, feldspathic
257'-262'	9'03"	0-2'11" — Sand, very light gray (N8), fine to coarse grained (some very coarse grains), quartzose, angular to subangular, micaceous, feldspathic 2'11"-9'3" — Clay, very light gray (N8) to pale greenish yellow (10Y8/2) to dusky red (5R3/4), slightly sandy
262'-265'	4'02"	0-4'2" — Clay, very light gray (N8) to pale greenish yellow (10Y8/2) to dusky red (5R3/4), slightly sandy
265'-485'	Washed	0-47' — Sand, medium to very coarse grained, quartzose, angular to sub-angular, slightly micaceous
485'-490'	4'09"	0-4'9" — Clay, moderate brown (5YR4/4) to greenish gray (5GY6/1) to yellowish gray (5Y7/2), sandy, silty. This unit contains some silty, very fine, quartzose, slightly feldspathic, sand sub-units
490'-493'	3'03"	0-3'3" — Clay, moderate brown (5YR4/4) to greenish gray (5GY6/1) to yellowish gray (5Y7/2), sandy, silty. This unit contains some sandy, very fine grained, quartzose, silty, slightly feldspathic sub-units
493'-540'	Wash	0-47' — Sand, very fine to very coarse grained, quartzose, angular to sub-angular, slightly micaceous
540'-554'	5'08"	0-4'0" — Sand, light gray (N7), very fine to coarse grained, quartzose, sub-angular, micaceous, feldspathic. This unit grades downward into: 4'0"-5'8" — Clay, mottled, light gray (N7) to moderate brown (5YR4/4) to light red (5R6/6), slight sandy
554'-555'	0'04.5"	0-4.5" — Clay, mottled, light gray (N7) to moderate brown (5YR4/4) to light red (5R6/6), slightly sandy
555'-570'	5'04"	0-2'3" — Clay, mottled, light gray (N7) to moderate brown (5YR4/4) to light red (5R6/6), slightly sandy 2'3"-5'4" — Silt, yellowish gray (5Y8/1), clayey, micaceous. This sub-unit grades downward into a sand, very fine grained, quartzose, micaceous
570'-580'	3'00"	0-3' — Clay, mottled, light gray (N7) to dusky yellow (5Y6/4) to moderate red (5R5/4), silty
580'-601'	3'10"	0-2'10" — Clay, light gray (N7), silty, micaceous. This unit grades downward into a sand, light gray (N7) with moderate yellowish orange (10YR7/6) staining, very fine grained, quartzose. This unit is in abrupt contact with:

Coring run	Recovered	Description
		2'10"-3'10" — Silty clay to silt, medium dark gray (N4), micaceous, lignitic, fossiliferous (lignitic plant remains)
601'-612'	5'02"	0-4'5" — Silty clay to silt, medium dark gray (N4), micaceous, lignitic, fossiliferous (lignitic plant remains). The lower 2'3" contains thin (0.25" or less) layers of sand, fine to very fine grained, quartzose
PIEDMONT		
		4'5"-5'2" — Weathered gneiss
612'-625'	4'11"	0-4'11" — Weathered gneiss
625'-635'	9'5"	0-9'5" — Weathered gneiss
635'-640'	3'11"	0-2'3" — Weathered gneiss
		2'3"-3'11" — Unweathered gneiss

APPENDIX B: Schematic construction of groundwater monitoring well. Source: Polyengineering Inc. (1995a).

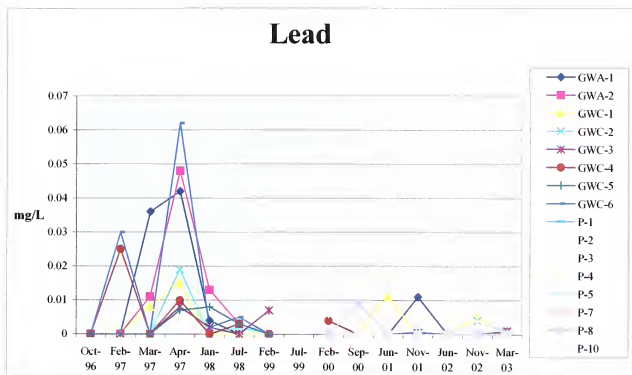


APPENDIX C: Subsurface drill log of GS-1. Source: Polyengineering Inc. (1995b).

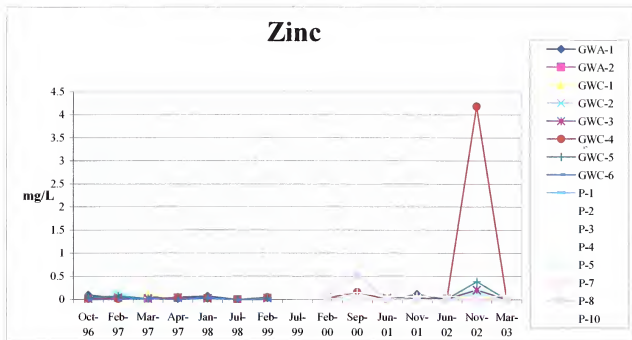
DEPTH	SOIL/MATERIAL DESCRIPTION	ELEVATION (feet)	LITHOLOGY	SPT BLOWS SAMPLES	WATER LEVEL	WELL DETAIL
6	SAND, Reddish Yellowish Brown, fine, very abundant fines	462		48		
				37		
7	CLAY, Reddish Brown, with trace of sand			34		
	SAND, Orangish Tan, very fine to coarse, micaceous, fining upward throughout this interval, last 0.1' Fe-stained, partially cemented	455		29		
14	Clay, Light Grayish Tan, micaceous, silty, minor lignite	448				
	SAND, Whitish Orange, very fine to medium/coarse, laminar Fe staining, continuous decrease in fine fraction with depth					
21	SAND, Orange, medium, wavy bedded, distinct Dark Fe staining from 22.9' to 23'	441				
	SAND, Orangish White, fine to medium, fines upward throughout this interval					
28	CLAY, Tannish Light Gray, lenticular to flaser-bedded (Decrease in clays with depth), Sand - Tan medium to coarse	434				
35	SAND, Orange, medium to coarse, clayey, flaser to wavy to lenticular bedding (fining downward), Purple Fe stained coarse sand lens from 35.0 to 35.5'	427				
	CLAY, Tan, massive drape					
42	SAND, Orangish White, medium, abundant matrix fines (app. 20%), decreasing to approx. 5% throughout this interval	420				
	SAND, Purple, coarse, well-sorted, clean					
49	CLAY, Tannish Light Gray, minor sand lenses (2-3 mm thick)					
	SAND, Tannish Orangish Purple, medium, bedding obscured by solution staining, minor discrete clay laminae, <i>Ophiomorpha</i> distinct	413				

DEPTH	SOIL/MATERIAL DESCRIPTION	ELEVATION (feet)	LITHOLOGY	SPT BLOWS SAMPLES	WATER LEVEL	WELL DETAIL
56	CLAY, Tannish Light Gray, lenticular-bedded sands					
	SAND, Orangish Reddish Purple, fine, well-sorted, micaceous, minor matrix clays (<10%)	406				
63						
		399				
	CLAY, Tannish Light Gray, massive micaceous with lenticular-bedded sands increasing with depth					
70	SAND, Orangish White, very fine, regular clay interlaminae (1-2 mm thick), clay fraction decreasing with depth. Sand highly Fe stained at 82'	392				
77						
		385				
84	CLAY, Tannish Light Gray, minor lenticular bedded sands					
	SAND, Reddish White, fine to medium, fines < 10%, coarsens downward throughout this interval, stained deep red at 90'	378				
91	SAND, Whitish Tan, medium to coarse, tabular bedding, <i>Ophiomorpha</i> sp. burrowed, coarsens downward throughout this interval	371				
98						
		364				
105	BORING TERMINATED AT 105 FEET CABLE BROKEN BORING CAVED UPON AUGER WITHDRAWAL BACKFILLED	357				

Appendix D-1: Lead concentrations over time. Unpublished data provided by CESAS.



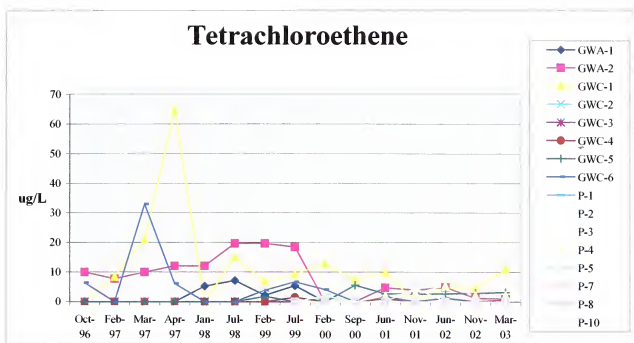
Appendix D-3: Zinc concentrations over time. Unpublished data provided by CESAS.



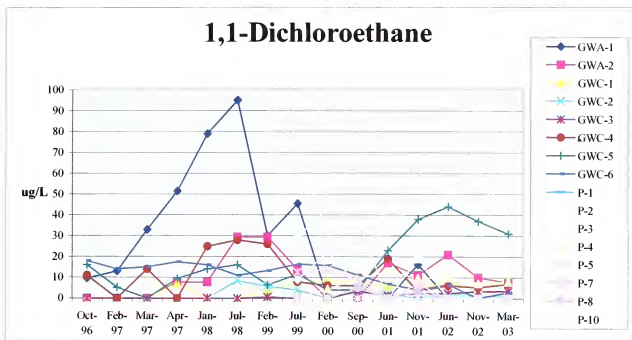
Appendix E-1: Methylene Chloride concentrations over time. Unpublished data provided by CESAS.



Appendix E-4: Tetrachloroethene concentrations over time. Unpublished data provided by CESAS.



Appendix E-6: 1,1-Dichloroethane concentrations over time. Unpublished data provided by CESAS.



Appendix E-7: Trichlorofluoromethane concentrations over time. Unpublished data provided by CESAS.

